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The Effects of Filter Configuration on Ion and Protein Separation Under Electric Fields in an Implantable Filter

Ali Ostadfar[1, 3], Will Cupples[2], Andrew Rawicz[1]

[1]School of Engineering Science, Simon Fraser University, Greater Vancouver, Canada
[2]Department of Biomedical Physiology and Kinesiology, Simon Fraser University, Greater Vancouver, Canada
[3]BC Children's Hospital Research Institute, University of British Columbia, Greater Vancouver, Canada

Email address
ali_ostadfar@sfu.ca (A. Ostadfar), wcupples@sfu.ca (W. Cupples), rawicz@sfu.ca (A. Rawicz)

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Abstract
This manuscript investigates on electromagnetic separation of ions and proteins in blood, in order to prevent their losses in the filtration procedure. Research team describe the experimental procedures used to determine separation dependence on electric field intensity (electro separation) in Y splitter and cross-flow electro separation. Researchers investigated experimentally the effect of operational parameters such as voltage and filtration methods on biofluids containing small electrolytes such as sodium and potassium electrolytes and proteins, largely albumin. The experiment modeled the human cardiovascular system by a cardiovascular pump, Y and crossflow methods for electro filtration. The electrodes and metallic mesh were used as electrical field operator to separate charged particles. Several electrical fields from 0.83 to 10 Kv/m were applied. The results demonstrate that with increase of voltage on electrodes and electrical field, the rate of separation increases for both ions and proteins. Considering the results, the performance of cross flow electro separation is better than Y splitter method.

1. Introduction

Each kidney in a human includes about 1 million nephrons, which are located on the cortex of the kidney. Each nephron includes the glomerulus and a long tubule. The tubule can select ions for reabsorption or secretion from the tubule wall, depending on body needs. In chronic kidney disease (CKD), patients lose large numbers of healthy nephrons permanently. In this condition, the patient must be under hemodialysis treatment [1]. In the earlier phases of this research on implantable artificial kidney investigators proposed a novel method of long term mechanical blood filtration using "back-wash" technique which utilizes the pulsating character of blood flow ([2],[3], [4]). The mechanical filtration (dialysis) is enabled through membranes with fine porosity and separates solids (blood cells) from plasma. All electrolytes and small proteins are lost and must be replenished intravenously. In implantable kidney this "lossy" character of filtration is intolerable. Research team propose another stage of blood filtration (or pre-filtration) which allows retention of electrolytes and small proteins by applying electrophoretic redirecting of ions and charged proteins away from mechanical filters. By redirecting

proteins away from filtration membranes, the team extend their functional life by reducing the probability of pore-clogging.

Electrophoresis is the motion of charged separated particles relative to a fluid under the influence of uniform electrical field. Researchers realized that the application of an electric field caused clay particles suspended in water to move. It happened because of the presence of a charged interface between surface of the particle and the water fluid. Michaelis invented and used the term electrophoresis in 1909 [5]. According to the nature of bio particles, several types of electric fields can be applied to manipulate them:

(1) A DC field for electrophoresis (EP) of charged bio particles [6]
(2) A non-uniform AC field for dielectrophoresis (DEP) of polarized (charged or neutral) bio particles ([7], [8], [9], [10]).
(3) Combined AC and DC fields for manipulating charged and neutral bio particles.

Several factors play key role in electrophoresis separation, such as media, viscosity, particle concentration, geometry of test, current, voltage, pH gradient and etc. [11]. Recently, Kohl et al. applied capillary electrophoresis in two-dimensional separation system by using at least one CE based separation techniques [12].

Figure 1 illustrates the electro filtration principle (electrophoresis) and particle manipulation by electrical field. The figure shows particle electrical charge and location of electrodes. The particle will move towards the opposite-charged electrode. In this paper, research team investigate the use of DC electric field for manipulation of ions and protein in a fluid circuit to separate them as an assistive or pre-filter method in blood filtration systems such as implantable artificial kidney.

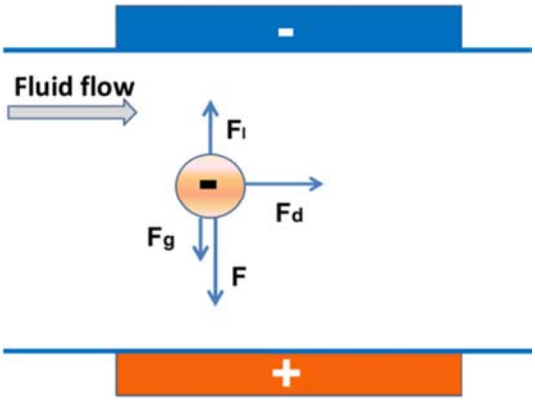

Figure 1. *Schematic of free body diagram for forces on charged particle in electrical field through fluid.*

Electrophoretic separations are based upon the fact that the electrical force (F) on a charged particle in an electrical field (E) is relative to the charge of the particle (q), or

$$F = q\,\mathrm{E} \tag{1}$$

In addition to this force, several forces such as drag (F_d), lift (buoyant) (F_l) and gravity (F_g) forces affect the trajectory of charged particle. Balancing of these forces define trajectory of particle and performance of separation. Figure 1 shows these forces on the particle in a moving fluid. Considering neglected amounts of gravity, lift or drag forces, the electrical force is the only considerable force as a dominant parameter in this experiment.

The heart produces a pulsatile flow to distribute blood to the body. A single dimensionless parameter called the Womersley's number [13] is an expression connecting a number of hydrodynamic parameters of liquid (blood). Reynolds number is another dimensionless number in fluidic system which helps to predict the transition between laminar and turbulent flows. Generally, this number in human body is less than 2000 (laminar flow<2000).

2. Experimental Method and Materials

2.1. Pulsatile Pump, Monitoring System and Power Supply

The COBE Century Perfusion Pump (COBE Cardiovascular Inc.) was used to provide the pulsatile flow in circulation. This pump is intended for use in cardiopulmonary surgical procedures or as an arterial pump in operating rooms. The test circuit was equipped with blood pressure transducers, PX272, (Edwards life sciences LLC) to measure fluid flow pressure. To provide a variety of voltages, a DC power supply (Heath, 2718 tri power supply) was used. A flame photometer (FLM3 flame photometer, Radiometer, Copenhagen) was used to measure concentration of ions. FLM3 is designed for fast and accurate quantitative determination of Na and K in serum/plasma and urine. To measure protein level the Qubit 2.0 Fluorometer was used. The Qubit 2.0 employs specifically designed fluorometric technology using Molecular Probesdyes and they bond to target molecule to measure concentration of target molecules.

2.2. Solution

For test solution, to simulate human blood levels of sodium and potassium electrolytes research team dissolved in deionized water NaCl and KCl with the relative concentrations ~140 Na /5 K. Bovine serum albumin (BSA) with molecular weight ~66.5 kDa was used to increase fluid viscosity and add Albumin protein for separation tests. The average concentration of the BSA in solutions was 4%.

2.3. Separation Modules

In this work, two geometries were used for ion and protein separation, "Y" splitter and the cross flow separation. In the "Y" splitter, the solution flow goes through the splitter and

two electrodes which are installed on splitter wall produce electrical field to change trajectory of particles, (Fig. 2). The electrodes are isolated from the liquid by Teflon foil and are connected to DC power supply.

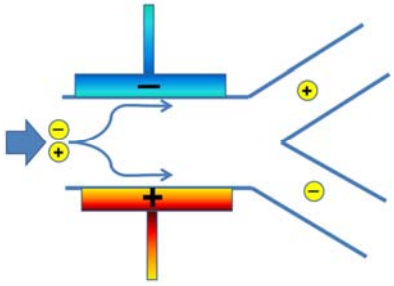

Figure 2. *Schematic of Y splitter and particle separation by electrical field.*

In cross flow electro separation, the flow passes above charged metallic filter (mesh) and this electrical charge repels the same charged particles from the mesh. The result is a different concentration of charged particles in permeate channel in comparison to inlet solution. Figure 3 illustrates electro separation by cross flow method. As the figure shows, because of negative potential of metallic filter, concentration of similar charged particles after mesh is lower than in the original solution. This method is analogous to kidney glomerulus filtration in Bowman capsule which filters whole blood from plasma by electromechanical separation. Figure 4 shows metallic mesh with wire diameter of 50μm.

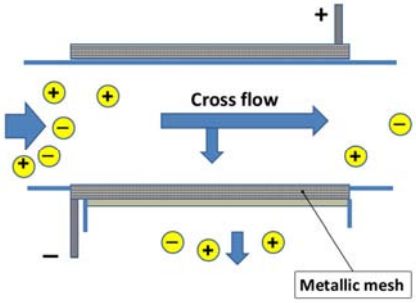

Figure 3. *schematic of cross flow electro separation.*

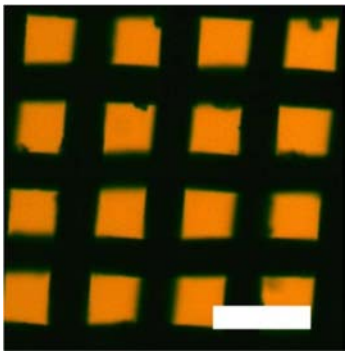

Figure 4. *Metallic mesh as electrode for electro separation. The unit bar is 100 micrometer.*

Figure 5 shows schematic of the test setup and arrangement of system. The Cobe pump produces pulsatile flow for system and the DC power supply generates electrical voltage for electrodes. In test setup, the "Y" splitter and cross flow separator are located in the separation module.

In all tests, the pump speed was one RPM to produce similar condition among examinations. The flow rate of the pump for this speed was around 2 ml/min.

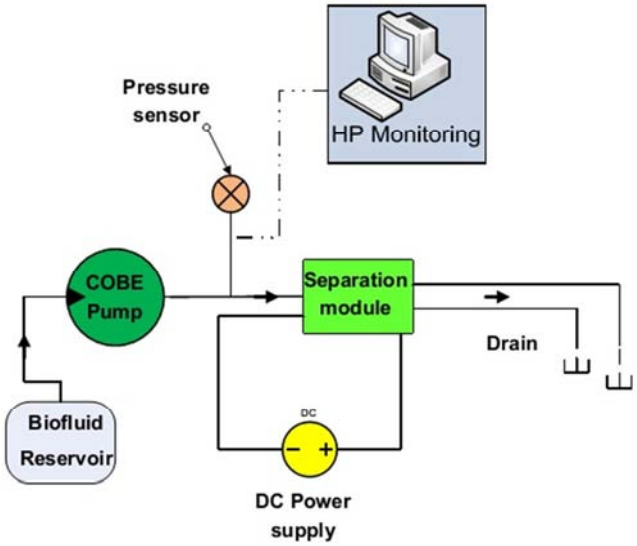

Figure 5. *Schematic of separation setup.*

Figures 6 and 7 show the separation modules, the "Y" splitter and the cross flow electro filtration used in experiment.

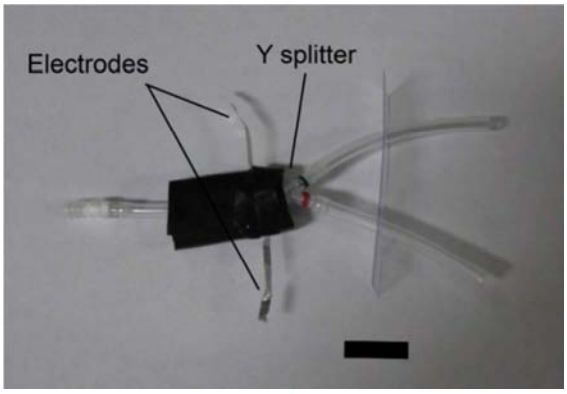

Figure 6. *"Y" splitter module, unit bar is 10 mm.*

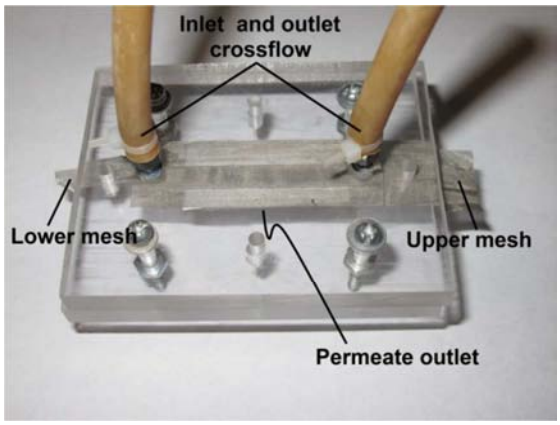

Figure 7. *Cross flow electro separation module.*

3. Results and Discussion

3.1. Ion Separation

The ions (Na, K) and the protein (Albumin) are separated from the solution by electric field. Several electric field intensities were used for electro separation. The experimental results of ion separation by presented methods are illustrated in figures 8 -16. Figures 8 and 9 show the results for "Y" splitter. As the figures show with increasing electrical field, the difference in concentrations of "Na" and "K" ions between outlets "N" (negative electrode side) and "P" (positive electrode side) is growing, The C letter shows the test or initial solution in experiment. The mean value of the two respective concentrations remains equal to the initial concentration.

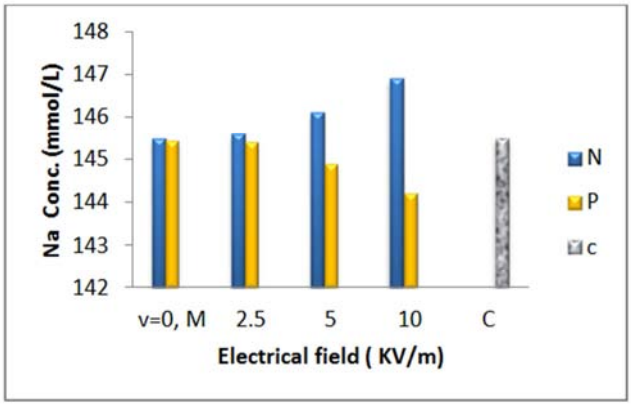

Figure 8. *Sodium concentration in Y splitter electro separation.*

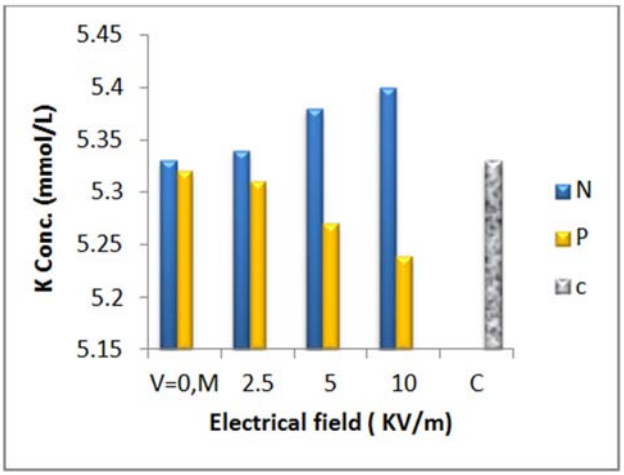

Figure 9. *Potassium concentration in Y splitter electro separation.*

Figures 10 and 11 illustrate results of cross flow for ion electro separation. The figures show that the separation rate is increased by increasing the electrical field between two electrodes for both sodium and potassium solutions. The open area in mesh filter was considered to be close to Y splitter channel cross section area to maintain the same test conditions for comparison. A comparison between figures demonstrates that the efficiency of cross flow electro separation is higher than in "Y" splitter method.

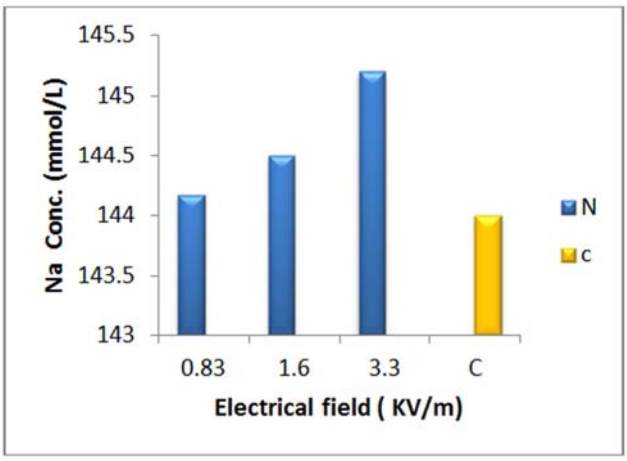

Figure 10. *Sodium concentration in cross flow electro separation.*

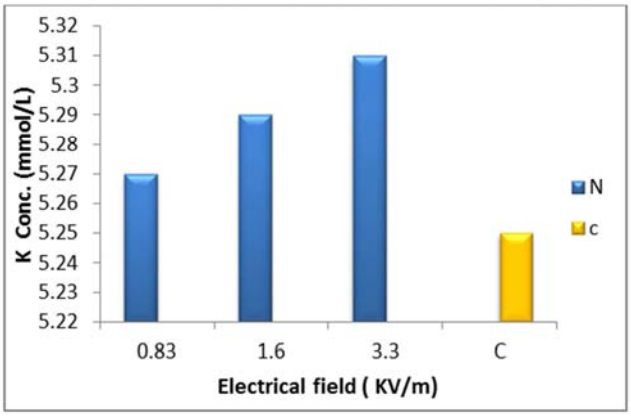

Figure 11. *Potassium concentration in cross flow electro separation.*

3.2. Protein Separation

Several values of electrical field were examined for protein separation in both "Y" splitter and cross flow methods. In the "Y" method such as ions experiments, with increasing electrical field, the difference in concentrations of protein between outlets is growing. Figure 12 shows the "Y" separation method results.

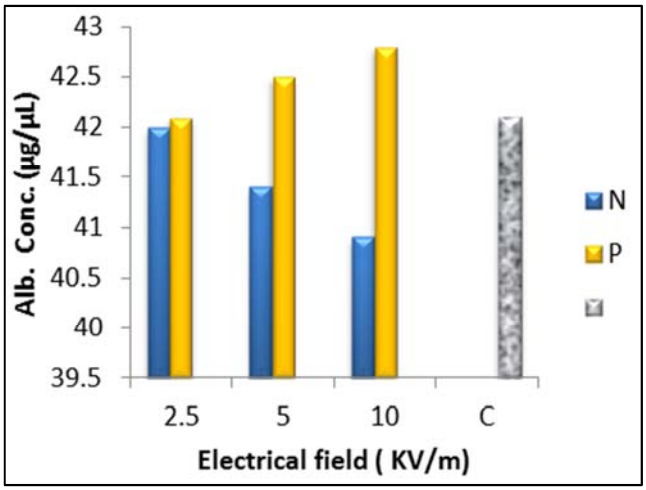

Figure 12. *Albumin concentration in Y splitter electro separation.*

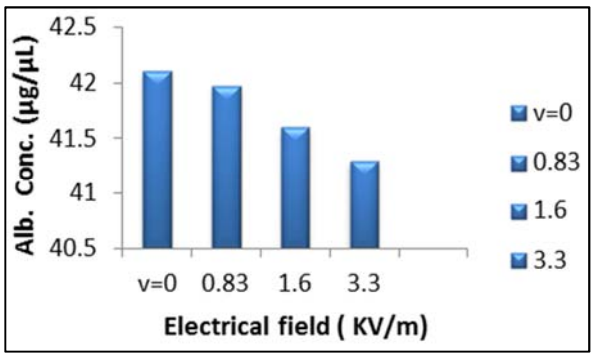

Figure 13. *Albumin concentration in cross flow electro separation.*

In cross flow method experiment, the metallic meshes were charged by negative (filter side) and positive potentials (wall side). Figure 13 shows that, by increasing the electrical field between meshes, the rate of albumin filtration decreased in the permeate side (the permeate mesh was negative potential). It means that the proteins were repelled from mesh surface with negative potential and continued their way by tangential flow on mesh to the outlet direction. The results follow trend behavior for these separations. Figures 12 and 13 illustrate performance of the separations for Y splitter and cross flow electro filtration, respectively.

Figures 14, 15 and 16 show a comparison between cross flow electro separation and Y splitter methods. Figures 14 and 15 illustrate that the cross flow electro separation has better performance than Y separation method for similar geometric parameters of open area of the Y channel and the metallic mesh of cross flow filtration.

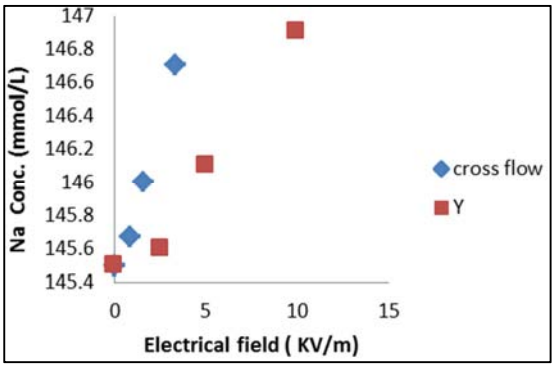

Figure 14. *Graph comparing between cross flow and Y electro separations for sodium.*

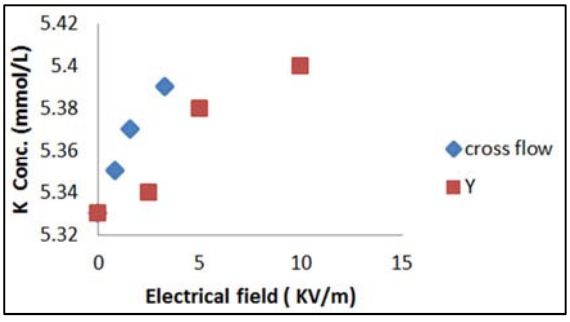

Figure 15. *Graph comparing between cross flow and Y electro separations for potassium.*

Figure 16 shows e comparison between cross flow and Y separation. Like the previous figures (Figs.14 and 15) this figure emphasizes the better performance of cross flow separation versus Y separation. In this experiment, the metallic mesh was charged by negative (filter side) and positive charges. By increasing electrical potential on mesh of filter side, the rate of albumin filtration decreased. This means that the proteins were repelled from the mesh with negative charge and the proteins preferred to continue their way by tangential flow.

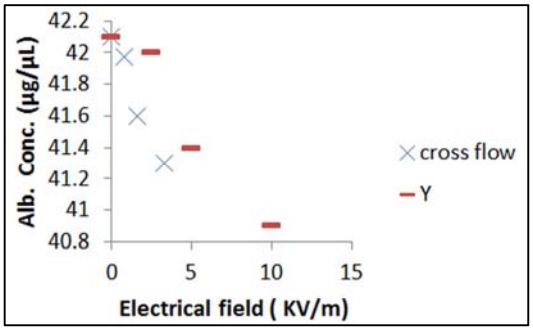

Figure 16. *Graph comparing between cross flow and Y electro separations for Albumin.*

4. Conclusion

This research was performed to study the separation of electrolytes (ions) and proteins in bio-fluids solutions by electric deviation.

Research team used cardiovascular pump to generate pulsatile flow in fluidic system to simulate pulsatile behaviour of blood in human body. For separation, the team introduced and tested two methods, Y splitter and cross flow. The resulting efficiencies of both methods were compared indicating cross-flow as superior in this experimental conditions.

Either method can be used to separate ions and proteins before the mechanical (glomerular) filtration takes over. The experimental results indicate that the efficiency of cross flow separation is higher than Y splitter although research team can use both methods to cover design limitations in implantable artificial separator. To provide full separation, research team are intending to use cascade methods to produce several stages of separation. This research and experiment help researchers and designers to have better view from this kind of separation and select the best structure for an implantable separator as an implantable artificial kidney.

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Funding: None
Ethical approval: Not required

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